A study of air velocity in a cooling

by Bambang Antoko

Submission date: 17-Apr-2020 10:08AM (UTC+0700)
Submission ID: 1299734764
File name: JMechE-Antoko1.docx (397.96K)
Word count: 1939
Character count: 9837

A study of air velocity in a cooling tower that affects the diameter of the droplet

*Bambang Antoko**
Politeknik Perkapalan Negeri Surabaya
**bambangantoko@ppns.ac.id*

Dany Iman Santoso
Universitas Negeri Surabaya

Ary Bachtiar Krishna Putra & Sutardi
Institut Teknologi Sepuluh Nopember

ABSTRACT

The study of air velocity inside the cooling tower gives an overview of the process of heat or mass transfer. Mathematical modeling based on the principle of continuity and statistical thermodynamics was developed to track changes in radius, velocity, density, and temperature of droplets and air along with the droplet trajectory or tower height. Before that, the droplet radius range is predicted in advance to get the accuracy of the calculation. Also, water capacity and fan rotation are varied to determine their effect on cooling tower performance. The calculation results show that the highest water capacity produces the highest efficiency. The highest efficiency indicates that the evaporation process occurs most efficiently. Mathematical modeling in calculations can also describe the increase in air temperature, which usually uses numerical simulations.

Keywords: *heat or mass transfer; mathematical modeling; statistical thermodynamics; droplet trajectory; tower height.*

Introduction

A cooling tower is a huge heat exchanger that has high effectiveness. Investigation about the phenomena of the fluids that work in it is an interesting thing to do. Observations were made to the level of droplets to get

ISSN 1823- 5514, eISSN 2550-164X
© 2018 Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM), Malaysia.
Received for review: 2017-03-03
Accepted for publication: 2018-03-03
Published: 2018-03-03

a high level of accuracy. Fluid interactions are described in the form of mathematical modeling obtained from governing equations.

In our two previous studies, we have analyzed the phenomenon of drifting or evaporation process. All are based on the movement of the droplet not only when it comes out of spray nozzles but also when it moves along the height of the tower. However, the movement of air that is sucked into the tower gets less attention. Therefore, in this study, the analysis is focused on obtaining air velocity along the trajectory and increasing or decreasing the temperature of working fluids due to the air movement.

Methods

The prediction of air velocity inside a cooling tower is derived from the continuity equation. From this, we obtain the maximum and average velocities of air used to calculate air velocity along the height of the tower using the principle of orifice area because the bottom of the cooling tower has a different area to the roof ($L^2 > A$), as shown in Figure 1.

Then, droplet diameter prediction is obtained from air and water spray velocities. From statistical thermodynamics, mathematical modeling is made to calculate the temperatures of the working fluids.

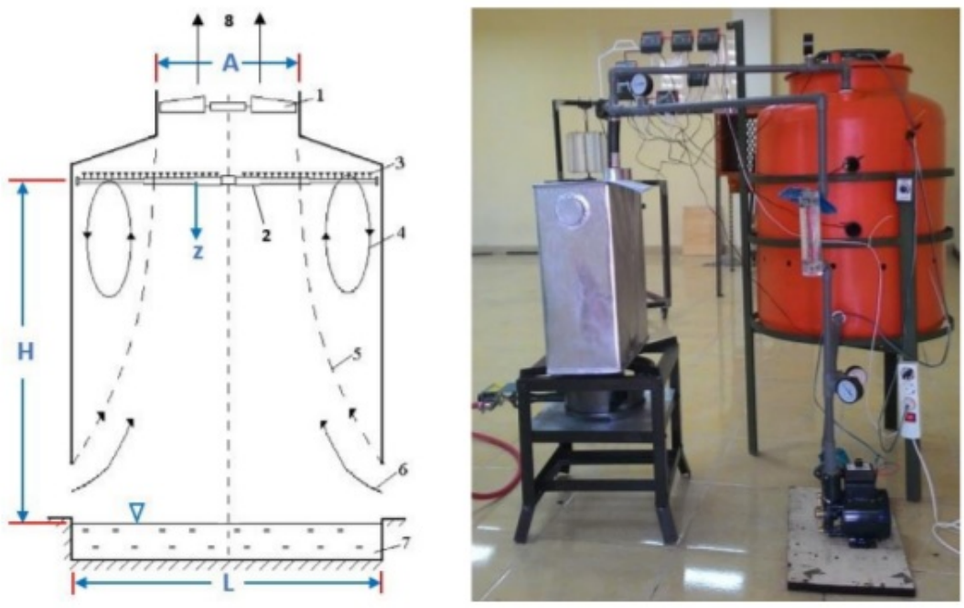

Figure 1: Scheme of the cooling tower: (1) Exhaust fan, (2) Delivery pipe, (3) Spraying nozzles, (4) Stagnation zone, (5) Line of stagnation zone, (6) Enter air, (7) Water basin, (8) Exit air.

Aerodynamics elements

Based on the movement of fluid that is sucked across the orifice, the velocity obtained is the average velocity. When it enters, the velocity is low, while when it exits, the velocity is high. Based on this phenomenon, the air velocity u is as

$$u = Q_a \big/ \left(\rho_a L^2\right) \tag{1}$$

These are the air capacity Q_a, the air density ρ_a, and the bottom diameter L.

Meanwhile, the maximum velocity of air $u_{\max}$ is obtained when it leaves the tower as

$$u_{\max} = Q_a \big/ \left(\rho_a A\right) \tag{2}$$

Where A is the roof cross-section area of the tower that is $A = \pi d_f^2 \big/ 4$ and d_f is the suction fan diameter. The velocity of droplet v is received from continuity at the nozzle as

$$v = \left(Q_w / A_n\right) - u \tag{3}$$

These are the water capacity Q_w and the nozzle cross-section area A_n that is $A_n = \pi d_n^2 \big/ 4$ where d_n is the nozzle diameter.

Because the bottom part with the roof tower resembles an orifice, non-uniform airflow is formed inside the cooling tower. The velocity of air $u(z)$ along the vertical z-axis is based on the principle of simple geometry as

$$u\left(z\right) \cong u_{\max} \frac{\pi\left(H-h\right)^2}{2\left[H-h+z\left(L\sqrt{\pi/2A}-1\right)\right]^2} \tag{4}$$

These are the height of the tower H, the height of the window h, and the position of observation z.

Model of the interactions

The size of the droplet radius depends on the velocity that affects it. In the principle of continuity, the greater the velocity, the smaller the radius. On the other hand, the temperature of the water that exits the nozzle also influences

the droplet surface tension. Surface tension is directly proportional to radius. From these two relationships, the droplet radius R is formulated as

$$R \leq 2.3 \frac{\sigma}{\rho_a u^2} \tag{5}$$

There is the water surface tension σ. From the relationship in Equation (5), a range of radius values is obtained. The maximum radius is achieved when the air velocity that moves upward and holds the droplet falling is also maximal whereas, the minimum radius received based on the velocity of the droplet falling relative to the average velocity of the air upwards.

In line with the principle of flow is a droplet with a large radius that has a large surface area as well, so that the drag force caused by the airflow is also getting bigger. As a result, the droplet will be carried out of the tower by air in the form of mass transfer because the droplet is still in the liquid phase. The range of droplet radius values can be seen in Figure 2.

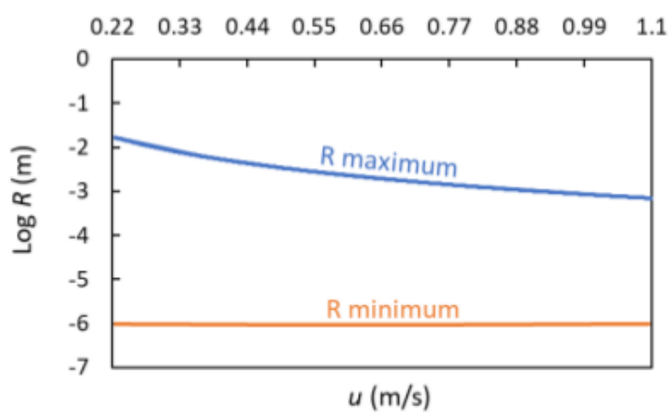

Figure 2: Droplet radius range values versus average air velocity.

Droplet velocity is much higher than air velocity even when compared to the maximum velocity. This is due to the effect of spraying on the nozzle, which causes high droplet velocity. Therefore, the possibility of droplet radius distribution is dominated by droplet velocity, as shown in Figure 3. From the distribution, the average value of the droplet radius is one-quarter of its range, to make it easier.

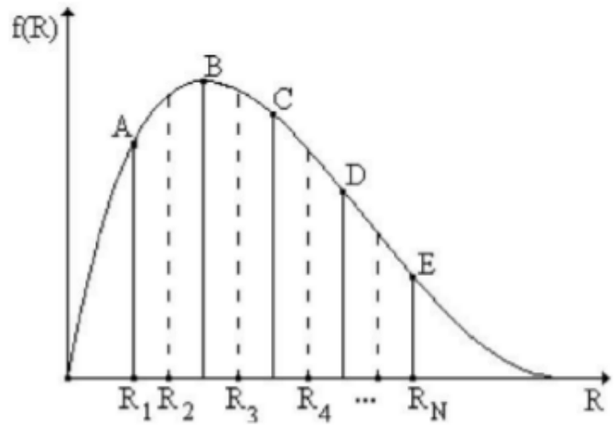

Figure 3: Probability distribution of droplet radius

The number of droplets N_d that exit in the spraying process depends on the water capacity, velocity, and diameter as

$$N_d(z) = \frac{3Q_w}{4\rho_w \pi R(z) v(z)} \tag{6}$$

These are the liquid water density ρ_w, the droplet radius $R(z)$ and velocity $v(z)$ along the z-axis. Some constants related to fluid flow are the Reynolds number Re, the heat transfer coefficient h, the mass transfer coefficient h_m, and the drag coefficient C_d shown by Equation (7), Equation (8), Equation (9), and Equation (10), respectively.

$$\mathrm{Re} = \frac{2\rho_a R(z)\left[v(z) - u(z)\right]}{\mu_a} \tag{7}$$

$$h = 2 + 0.5\,\mathrm{Re}^{0.5} \tag{8}$$

$$h_m = \frac{D\left(2 + 0.5\,\mathrm{Re}^{0.5}\right)}{2R(z)} \tag{9}$$

$$C_d = \frac{24}{\mathrm{Re}}\left(1 + \frac{\mathrm{Re}^{2/3}}{6}\right) \tag{10}$$

These are the coefficient of diffusion for water vapor D and the air dynamic viscosity μ_a.

Then, the mathematical model that calculates interactions between water and air in the form of changes in droplet radius $R(z)$, droplet fall velocity $v(z)$, droplet temperature $T_w(z)$, air temperature $T_a(z)$, and droplet density $\rho(z)$ along the z-axis is presented by Equation (11), Equation (12), Equation (13), Equation (14), and Equation (15), respectively.

$$\frac{dR(z)}{dz} = -\frac{h_m\left[\rho_s\left(T_w(z)\right)-\rho(z)\right]}{\rho_w v(z)} \tag{11}$$

$$\frac{dv(z)}{dz} = \frac{g}{v(z)} - C_d \frac{\rho_a\left[v(z)-u(z)\right]^2}{2v(z)} \frac{\pi R(z)^2}{m} \tag{12}$$

$$\frac{dT_w(z)}{dz} = \frac{3\left\{h\left[T_a(z)-T_w(z)\right]-h_m\left[r-c_w T_w(z)\right]\left[\rho_s\left(T_w(z)\right)-\rho(z)\right]\right\}}{c_w \rho_w R(z) v(z)} \tag{13}$$

$$\frac{dT_a(z)}{dz} = \frac{4\pi}{\rho_a c_a} \frac{R(z) N_d(z)}{v(z)-u(z)} h\left[T_w(z)-T_a(z)\right] \tag{14}$$

$$\frac{d\rho(z)}{dz} = -4\pi \frac{R(z)^2 N_d(z)}{v(z)-u(z)} h_m\left[\rho_s\left(T_w(z)\right)-\rho(z)\right] \tag{15}$$

These are the saturated water vapor density ρ_s, the water specific heat c_w, the air specific heat c_a, and the latent heat of vaporization r.

From Equation (7) to Equation (15), they are not independent but depend on each other. Therefore, boundary conditions are needed to start the calculation in the form of initial values. The following are the initial values for each parameter but, keep in mind that the position $z = 0$ for water and air is different because this cooling tower is of counter flow type.

At $z = 0$ (the point of water exits the nozzles):
the droplet radius

$$R\big|_{z=0} = R_0 \tag{16}$$

the droplet velocity

$$v\big|_{z=0} = v_0 \tag{17}$$

the droplet temperature

$$T_w\big|_{z=0} = T_{w0} \tag{18}$$

At $z = H$ (the point of air enters the windows):
the air temperature

$$T_a\big|_{z=H} = T_{a0} \tag{19}$$

the water vapor density

$$\rho\big|_{z=H} = \rho_0 \tag{20}$$

With these initial value definitions, a nonlinear boundary-value problem system is formed from ordinary differential equations which are Equation (11) to Equation (15).

The last thing to count is the performance of the cooling tower in the form of efficiency. As previously identified, the limitation of the system is the ambient air temperature entering the tower in the form of atmospheric temperature or temperature limit $T_{\lim}$. The efficiency η becomes

$$\eta = \frac{T_{w0} - T_{wf}}{T_{w0} - T_{\lim}} \tag{21}$$

Where T_{wf} is the water average temperature in the water basin. The temperature limit can also be used to calculate air humidity in a cooling tower as

$$\rho_s\left(T_a\right) \cdot \psi = \rho_s\left(T_{\lim}\right) \tag{22}$$

Where ψ is the air relative humidity.

Results and discussions

Cooling tower dimensions in the experiment are presented in Table 1. The water capacity and fan rotation are varied to obtain variations in droplet and air velocities. Also, we have determined the capacity calculated based on previous studies: 0.5 Lpm (minimum), 6.0 Lpm (equilibrium), and 18 Lpm (maximum).

Table 1: The cooling tower dimensions

Dimensions	Value	Units
Tower height (H)	0.56	meter (m)
Bottom diameter (L)	0.65	meter (m)
Windows height (h)	0.20	meter (m)
Fan diameter (d_f)	8.0	inch (in)
Nozzle diameter (d_n)	0.001	meter (m)
Water capacity	0.5 – 18	Liter per minute (Lpm)
Fan rotation	300 – 1500	rotation per minute (rpm)

Changes in the droplet radius, as shown in Figure 4, undergo the highest decrease for the lowest capacity. Even though, from the count, the lowest capacity has the largest radius. The same thing is also presented by the graphs of the change in velocity droplet, as shown in Figure 5, where the lowest capacity also has the highest velocity change, however, the initial velocity is the lowest.

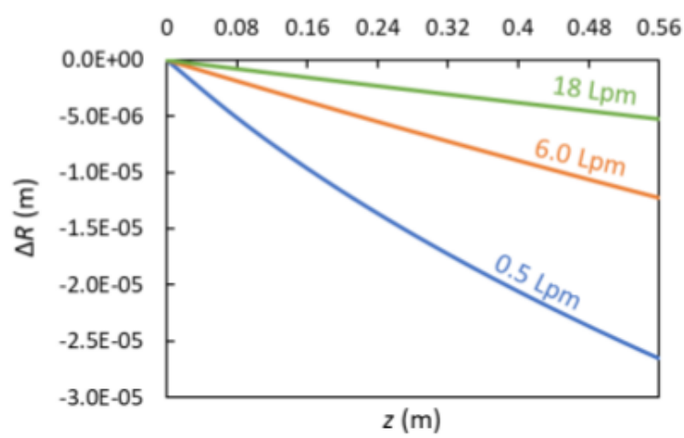

Figure 4: Droplet radius changes along its vertical trajectory.

Low water capacity has low momentum, so some of the water may be carried by the airflow, because this is a counterflow, in the form of a liquid phase. This reduction can also be observed through the graphs of changes in vapor density in Figure 6. It appears that the lowest capacity has the highest reduction in density, and there is indeed a reduction in the mass of the droplet while crossing the airflow.

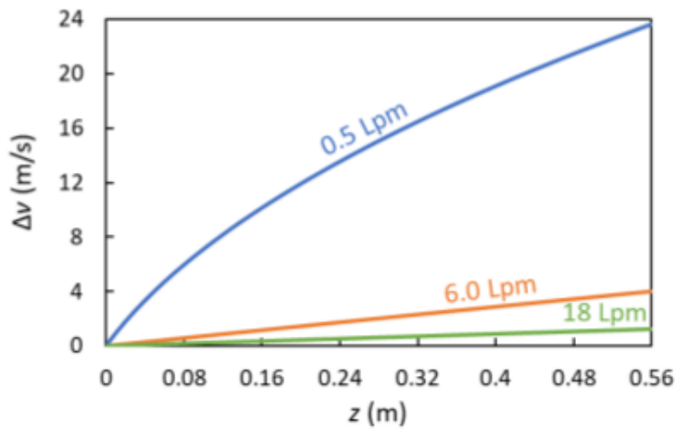

Figure 5: Changes in velocity of falling droplets along its trajectory.

Whereas for high capacity graphs, both 6.0 Lpm and 18 Lpm in Figure 6, the vapor density tends to remain. This indicates a mass reduction at high capacity relatively small.

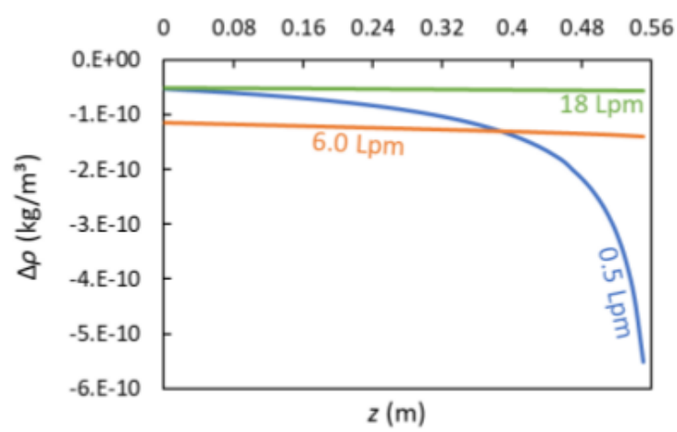

Figure 6: Reduction of vapor density along the droplet trajectory.

The highest droplet temperature reduction is achieved by the lowest capacity, as shown in Figure 7. Similarly, the highest increase in air

temperature is also given by the lowest capacity, as illustrated in Figure 8. Both temperatures are the result of interactions within the tower.

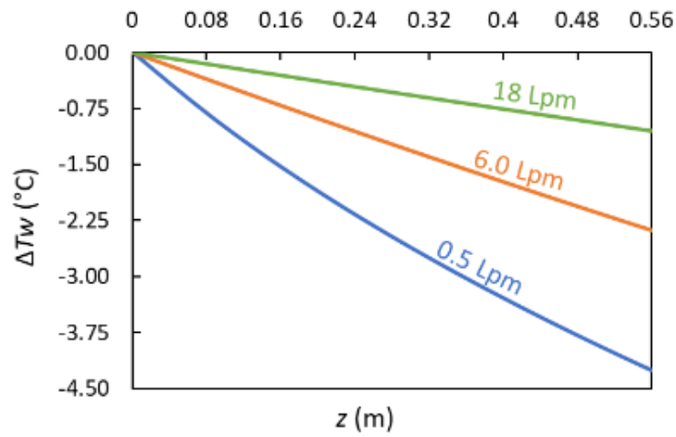

Figure 7: Decreased droplet temperature along its trajectory.

High water capacity carries high mass water flow so that, with the same tower volume, it provides higher density, which causes lower temperature changes. By the same airflow capacity, it produces lower air temperature enhancements, as seen in Figure 8.

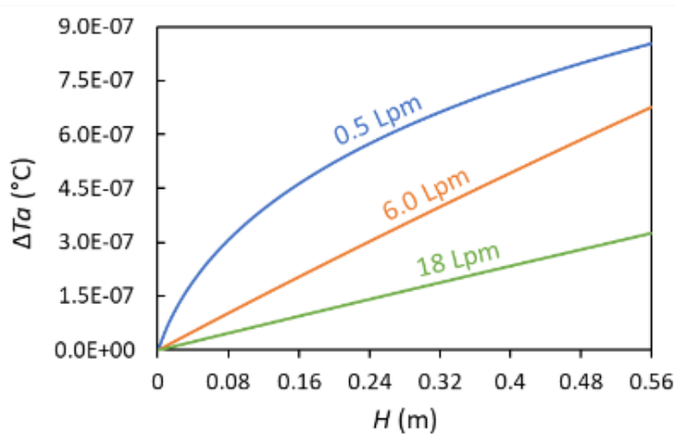

Figure 8: Increased air temperature along the tower height.

The same thing with air temperature is indicated by relative humidity, as shown in Figure 9. Humidity increases indicating that the water content in the air also increases.

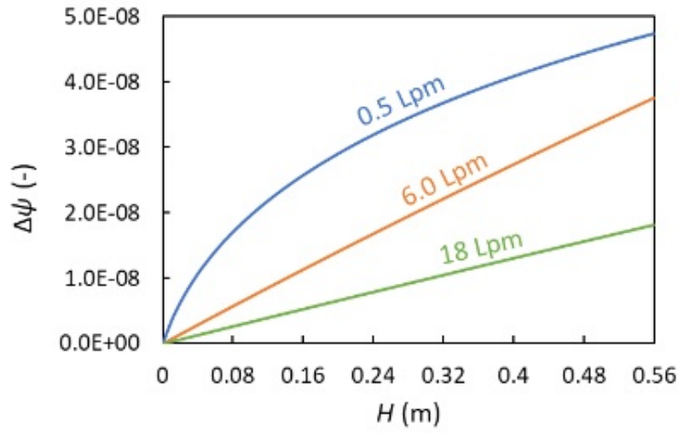

Figure 9: Increased relative humidity along the tower height.

Variations in fan rotation provide variations in the velocity of air across the tower. Figure 10 describes the variation in the form of velocity along with the tower height.

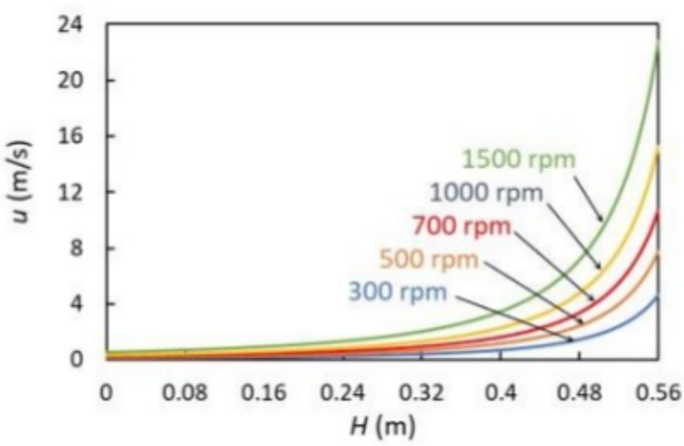

Figure 10: Air velocity along with tower height.

The evaporation process is reflected in the performance graphs presented in Figure 11. From this graph, the highest capacity has the highest efficiency, which means that the heat transfer process occurs most efficiently at the highest capacity. A high mass flow rate of water accelerates the distribution of droplets to move heat into the air.

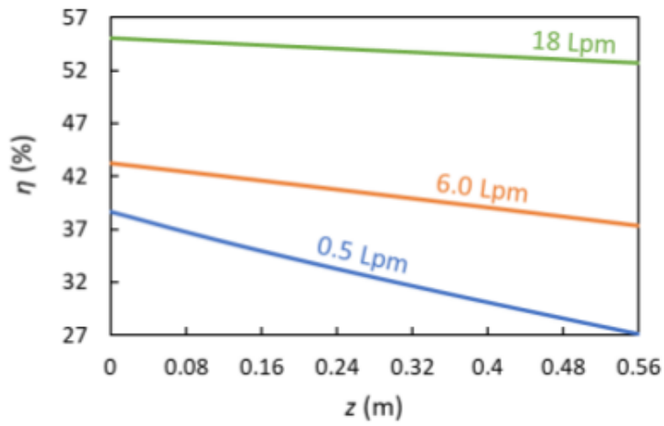

Figure 11: The cooling tower efficiency along the droplet trajectory depends on the water capacity.

Conclusions

The lowest water capacity produces the highest changes in droplet radius, velocity, density, and temperature, but it generates the lowest performance. The lowest performance means the highest losses in the form of drifting for the droplet mass, which is still in a liquid phase. The air velocity reaches its maximum when it exits the tower, as well as its temperature and humidity.

A study of air velocity in a cooling

ORIGINALITY REPORT

3%	2%	1%	3%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Submitted to Universiti Teknologi MARA Student Paper	2%
2	www.emeraldinsight.com Internet Source	1%
3	www.waset.org Internet Source	<1%

Exclude quotes	Off	Exclude matches	Off
Exclude bibliography	Off		